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OTHER AUTHORS
John Armstrong

☐ Premeeting publication
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# Synthetic LISA

## simulating time-delay interferometry in a model LISA


(presenting) Michele Vallisneri
(in absentia) John W. Armstrong
LISA Science Office, Jet Propulsion Laboratory


12/17/2003

# Why Synthetic LISA?

- Simulate LISA fundamental noises
  at the level of science/technical requirements
  - Higher level than extended modeling (no spacecraft subsystems)
  - Lower level than data analysis tools (do time-domain simulation of TDI; include removal of laser frequency fluctuations)
- Provide streamlined module to filter GWs through TDI responses, for use in developing data-analysis algorithms
  - Include full model of TDI
    (motion of the LISA array, time- and direction-dependent armlengths, causal Doppler observables, 2nd-generation TDI observables)
  - Use directly or to validate (semi)analytic approximations
- Make it friendly and fun to use

# A LISA block diagram (very high level!)

**GW sources**

for plane waves, work from **k**, $h_+(t)$, $h_\times(t)$ at SSB

**LISA noises**

laser freq. fluctuations,
(optical bench),
proof mass, optical path

**LISA geometry**

spacecraft positions
→ photon propagation
→ armlengths

**Doppler $y_{ij}$**

inter-spacecraft relative frequency fluctuations

**Doppler $z_{ij}$**

intra-spacecraft relative frequency fluctuations

**TDI observables**

time-delayed combinations of $y_{ij}$ and $z_{ij}$

laser-noise and optical-bench-noise free

3 independent observables

# A LISA block diagram (very high level!)

$$
\begin{aligned}
X = {} & y_{32,322} - y_{23,233} - y_{31,22} - y_{21,33} + y_{23,2} - y_{32,3} + y_{21} - y_{31} \\
& -\frac{1}{2}(-z_{21,2233} + z_{21,33} + z_{21,22} - z_{21}) \\
& -\frac{1}{2}(+z_{31,2233} - z_{31,33} - z_{31,22} + z_{31})
\end{aligned}
$$

**Doppler $y_{ij}$**

inter-spacecraft relative frequency fluctuations

**Doppler $z_{ij}$**

intra-spacecraft relative frequency fluctuations

**TDI observables**

time-delayed combinations of $y_{ij}$ and $z_{ij}$

laser-noise and optical-bench-noise free

3 independent observables

$$
\begin{aligned}
\alpha = {} & y_{21} - y_{31} + y_{13,2} - y_{12,3} + y_{32,12} - y_{23,13} \\
& -\frac{1}{2}(z_{13,2} + z_{13,13} + z_{21} - z_{21,123} + z_{32,3} + z_{32,12}) \\
& +\frac{1}{2}(z_{23,2} + z_{23,13} + z_{31} - z_{31,123} + z_{12,3} + z_{12,12})
\end{aligned}
$$

# A LISA block diagram (very high level!)

**GW sources**

for plane waves, work from **k**, $h_+(t)$, $h_\times(t)$ at SSB

**Doppler $y_{ij}$**

inter-spacecraft relative frequency fluctuations

**Doppler $z_{ij}$**

intra-spacecraft relative frequency fluctuations

photon propagation vector

GW TT tensor

$$\Psi_l(t) = \frac{\hat{n}_l \cdot \mathbf{h}(t) \cdot \hat{n}_l}{2[1 - (\hat{k} \cdot \hat{n}_l)^2]}$$

geom. projection factor

Doppler shift due to GWs (Wahlquist-Estabrook response) measured for reception at spacecraft r and emission at spacecraft s (laser travels along arm l)

GW buffeting of spacecraft s at emission $(t-L_l)$

GW buffeting of spacecraft r at reception $(t)$

geom. projection factor

wavefront retard.; $p_i$ are spacecraft pos.

$$y^{\mathrm{gw}}_{lr}(t) = y_{(s)lr}(t) = \left[1 + \epsilon_{slr} \hat{k} \cdot \hat{n}_l\right] \left(\Psi_l(t - \hat{k} \cdot \vec{p}_s - L_l) - \Psi_l(t - \hat{k} \cdot \vec{p}_r)\right)$$

# A LISA block diagram (very high level!)

Doppler shift measured for reception at spacecraft 1 and emission at spacecraft 3 (laser travels along arm 2)

fluctuations of laser 3 at emission (t - $L_2$)

fluctuations of laser 1* (reference) at reception (t)

$$y_{21} = C_{3,2} + 2pm_1^* - C_1^* + y_{21}^{\text{opt path}}$$

proof-mass 1* noise

shot noise at sc 1

## LISA noises

laser freq. fluctuations,
(optical bench),
proof mass, optical path

**Doppler $y_{ij}$**
inter-spacecraft relative frequency fluctuations

**Doppler $z_{ij}$**
intra-spacecraft relative frequency fluctuations

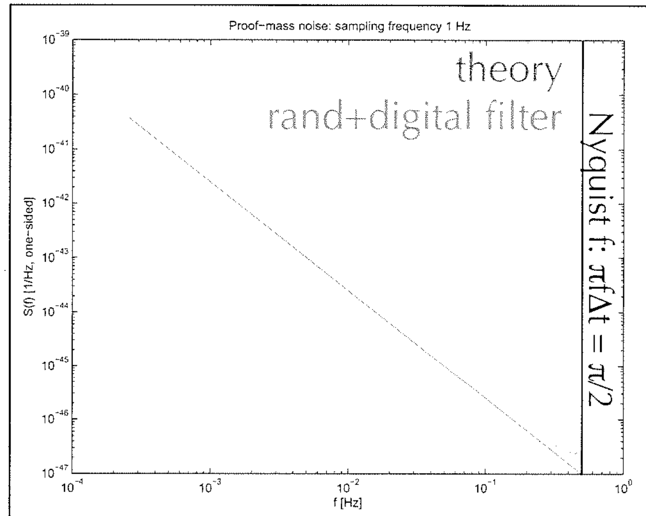
Doppler shift measured between optical benches on spacecraft 1

proof-mass 1 noise

$$z_{21} = C_1 + 2pm_1 - C_1^*$$

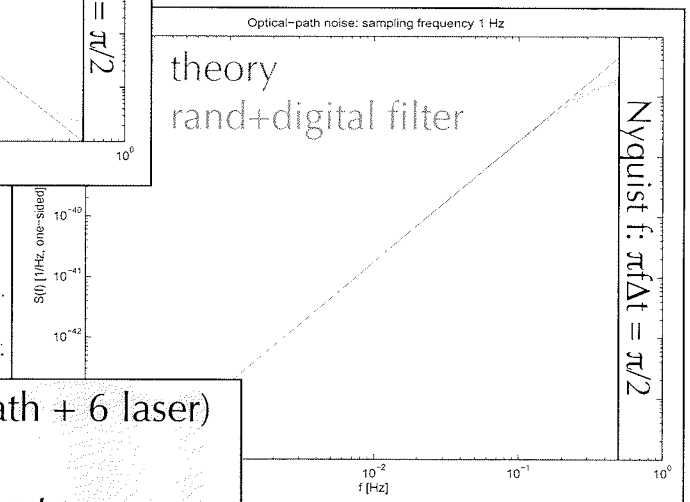
fluctuations of lasers 1 and 1*

# A LISA block diagram (very high level!)




## LISA noises

laser freq. fluctuations,
(optical bench),
proof mass, optical path




**LISA noises**: 18 time series (6 proof mass + 6 optical path + 6 laser)

- Assume Gaussian, $f^{-2}$, $f^{2}$, white
- Generate in the time domain by applying digital filters to uncorrelated white noise produced at fixed sampling time, then interpolate
- For laser noise, use combination of Markov chain ($\exp(-\Delta t/\lambda)$ correlation) and low-pass digital filter

# A LISA block diagram (very high level!)

**Motion complicates GW signals (1):**
- by changing orientation of LISA plane (power spread through ~9 bins)
- by Doppler-shifting incoming GW signals (due to relative motion, dominates for $f > 10^{-3}$ Hz; bandwidth ~$(\Omega R/c)f$)

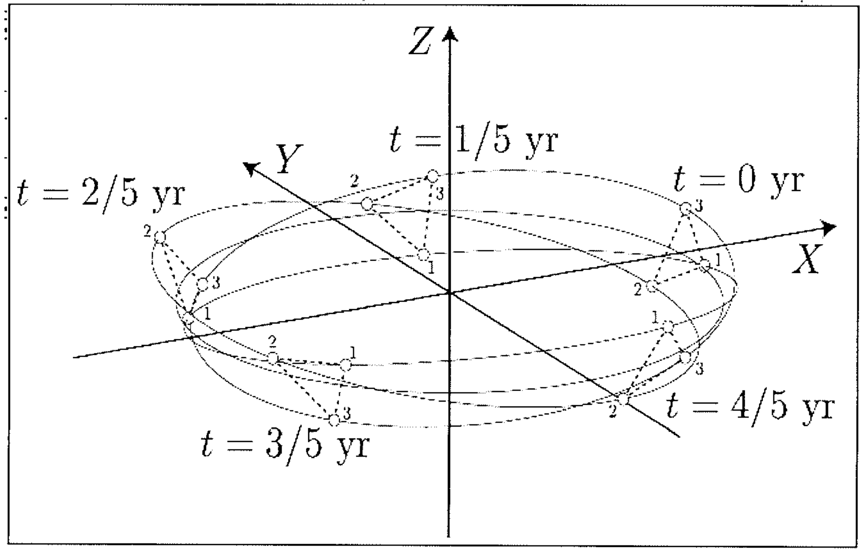
1. One Solar orbit/yr; LISA triangle spins through 360°/orbit
2. Armlengths deviate from equilateral triangle at ~2%
3. Armlengths are time and direction dependent

**Motion improves sensitivity to GW (1):**
- to source position and polarization
- makes it homogeneous in the sky

**Motion hinders noise suppression (1,2,3):**
- need accurate knowledge of armlengths
- high-order time delays needed

LISA geometry

spacecraft positions
→ photon propagation
→ armlengths



# The Synthetic LISA package

Implements the LISA block structure as a collection of C++ classes

## Class **LISA**

Defines the LISA time-evolving geometry (positions of spacecraft, armlengths)

**OriginalLISA**: static configuration with fixed (arbitrary) armlengths

**ModifiedLISA**: stationary configuration, rotating with T=1yr; different cw and ccw armlengths

**CircularRotating**: spacecraft on circular, inclined orbits; cw/ccw, time-evolving, causal armlengths

**EccentricInclined**: spacecraft on eccentric, inclined orbits; cw/ccw, time-evolving, causal armlengths

**NoisyLISA** (use with any **LISA**): adds white noise to armlengths used for TDI delays

...

## Class **Wave**

Defines the position and time evolution of a GW source

**SimpleBinary**: GW from a physical monochromatic binary

**SimpleMonochromatic**: simpler parametrization

**InterpolateMemory**: interpolate user-provided buffers for $h_+$, $h_x$

...

## Class **TDI**(LISA,Wave)

Return time series of noise and GW TDI observables (builds causal $y_{ij}$'s; includes 1st- and 2nd-generation observables)

**TDInoise**: demonstrates laser-noise subtraction

**TDIsignal**: causal, validated vs. *LISA Simulator*

**TDIfast**: cached for multiple sources (Edlund)

# The Synthetic LISA package

...things to do with it right now!

## Class **LISA**

Defines the LISA time-evolving geometry (positions of spacecraft, armlengths)

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...

## Class **Wave**

Defines the position and time evolution of a GW source

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**SimpleMonochromatic**: simpler parametrization

**InterpolateMemory**: interpolate user-provided

...

Check the sensitivity of alternate LISA configurations

## Class **TDI**(LISA,Wave)

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**NoisyLISA** (use with any **LISA**): adds white noise to armlengths used for TDI delays

...

## Demonstrate laser-noise sub.:

- 1st-generation TDI
- modified TDI
- 2nd-generation TDI
- degradation of subtraction for imperfect knowledge of arms
- with armlocking

## Class **TDI**(LISA,Wave)

Return time series of noise and GW TDI observables (builds causal $y_{ij}$'s; includes 1st- and 2nd-generation observables)

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# The Synthetic LISA package

...things to do with it right now!

## Class **LISA**

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**Produce synthetic time series to test data-analysis algorithms**

**ModifiedLISA**: stationary configuration, rotating with T=1yr; different cw and ccw armlengths

**CircularRotating**: spacecraft on circular, inclined orbits; cw/ccw, time-evolving, causal armlengths

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Return time series of noise and GW TDI observables (builds causal $y_{ij}$'s; includes 1st- and 2nd-generation observables)

**TDInoise**: demonstrates laser-noise subtraction

**TDIsignal**: causal, validated vs. *LISA Simulator*

**TDIfast**: cached for multiple sources (Edlund)

# Using Synthetic LISA

The preferred interface to Synthetic LISA is through a simple script in the language Python.

This is a Python script!

Import the Synthetic LISA library (lisaswig.py, _lisaswig.so) so we can use it

```
#!/usr/bin/python

import lisaswig;
```

Create a LISA (geometry) object; use static LISA, with unequal arms

```
unequalarmlisa = lisaswig.OriginalLISA(15.0,16.0,17.0);
```

Armlengths (s)

Create a TDI object based on our chosen LISA

```
unequalarmnoise = lisaswig.TDInoise(unequalarmlisa,
        1.0,2.5e-48,1.0,1.8e-37,1.0,1.1e-26,1.0);
```

Laser correlation (s)

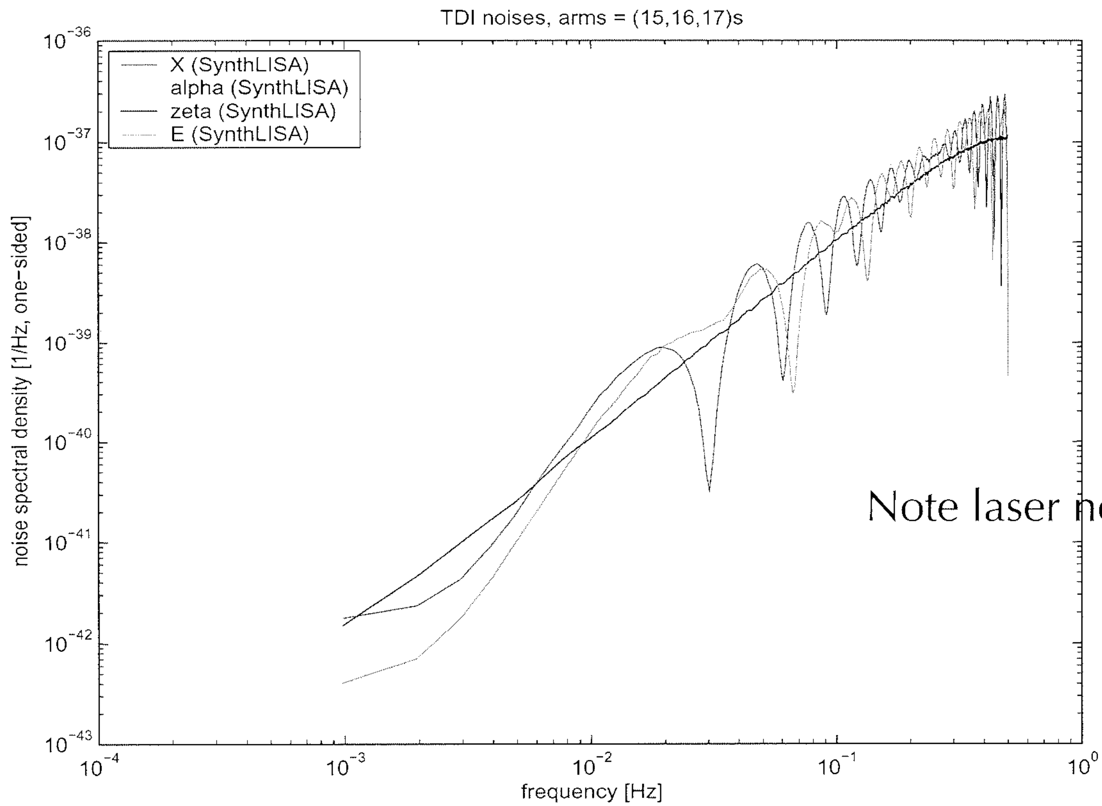
Noise sampling time (s)

Proof mass $S_n \times f^2$ ($Hz^{-1}$)   Opt. path $S_n \times f^{-2}$ ($Hz^{-1}$)   Laser $S_n$ ($Hz^{-1}$)

```
lisaswig.printtdi("noise-X.txt",unequalarmnoise,1048576,1.0,"X");
```

Print X TDI noise to disk!   File name   # samples requested, sampling time   TDI variables to print

# Example: unequal-arm 1st-gen. noises

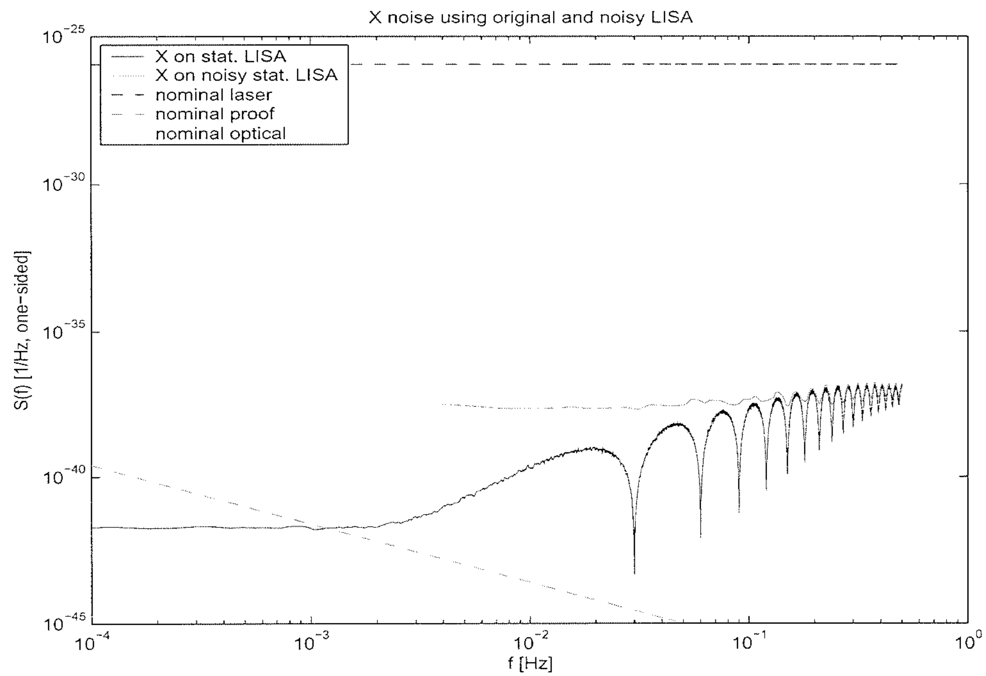



$10^{-25}$

Note laser noise subtraction!

```
...
lisaswig.printtdi("noise-a.txt",unequalarmnoise,1048576,1.0,"a");
lisaswig.printtdi("noise-z.txt",unequalarmnoise,1048576,1.0,"z");
lisaswig.printtdi("noise-E.txt",unequalarmnoise,1048576,1.0,"E");
```

# Example: noisyLISA subtraction

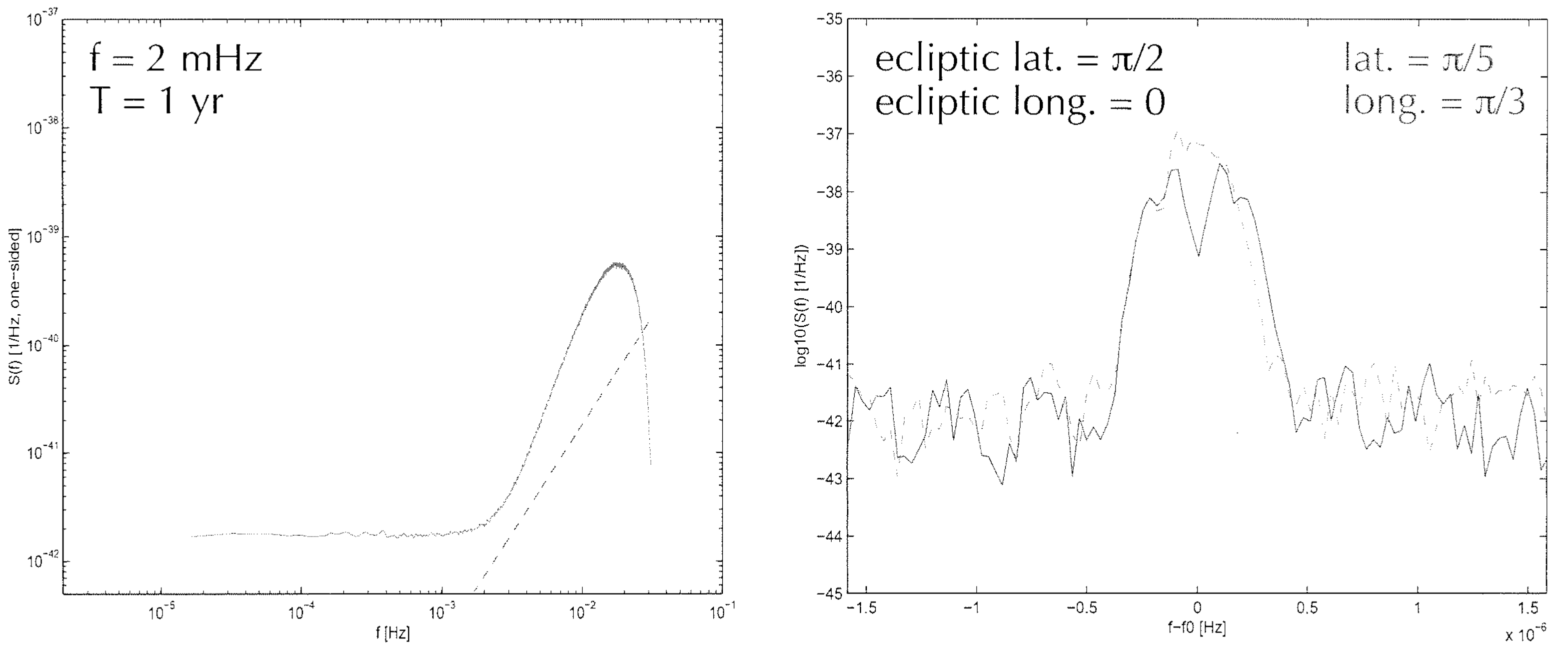



```
originallisa = lisaswig.OriginalLISA(16.6782,16.6782,16.6782)

noisylisa = lisaswig.NoisyLISA(originallisa,1.0,measurement noise)

originalnoise = lisaswig.TDInoise(originallisa,
                  1.0,2.5e-48,1.0,1.8e-37,1.0,1.1e-26,0.1)
noisynoise = lisaswig.TDInoise(noisylisa,originallisa,
                  1.0,2.5e-48,1.0,1.8e-37,1.0,1.1e-26,0.1)
```

measurement noise $S_n$ ($s^2$ $Hz^{-1}$)

Use different LISA for noise and TDI delays

# Example: monochromatic binary

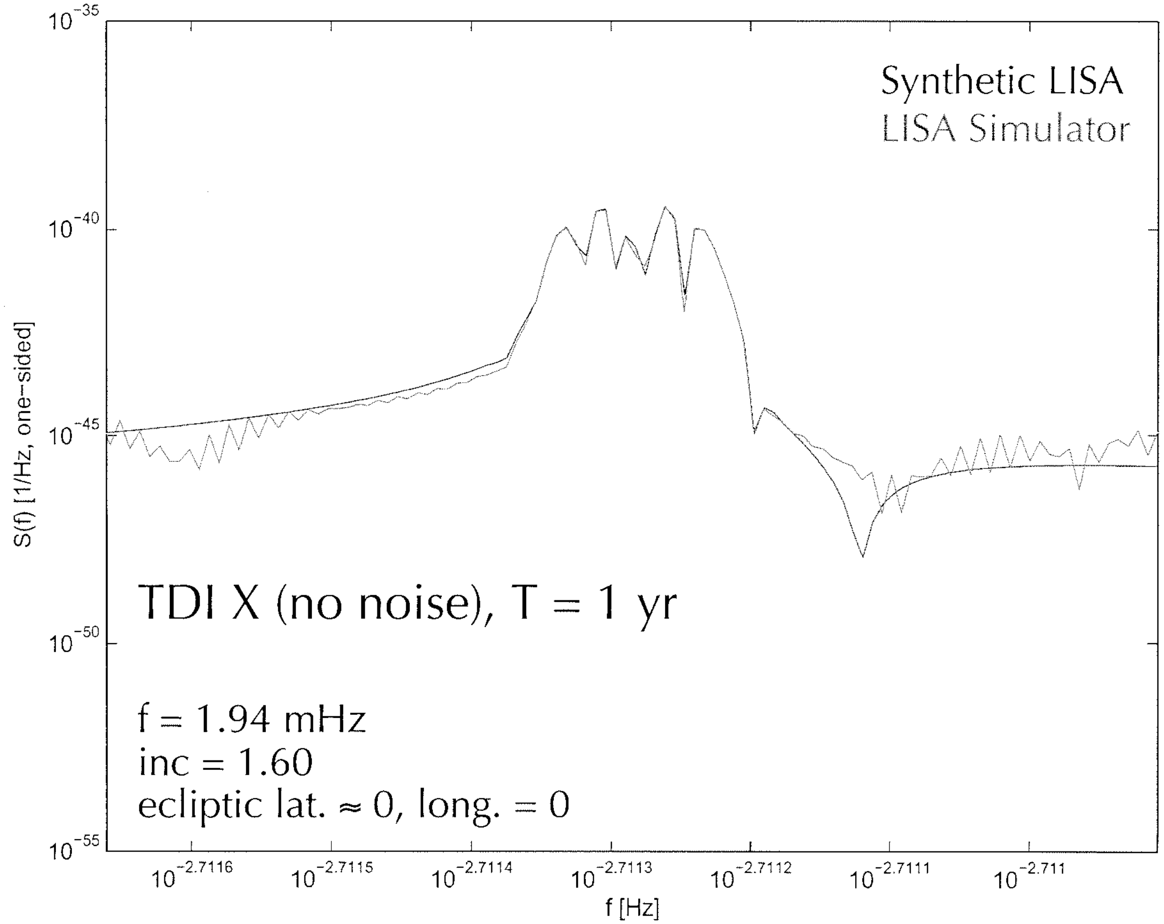



```
mylisa = lisaswig.CircularRotating(0.0,0.0,1.0)
mybinary = lisaswig.SimpleBinary(frequency,initial phase,inclination,amplitude,
             ecliptic latitude,ecliptic longitude,polarization angle)
mysignal = lisaswig.TDIsignal(mylisa,mybinary)
lisaswig.printtdi("signal-X.txt",mysignal,secondsperyear/16.0,16.0,"X")
```

LISA array parameters

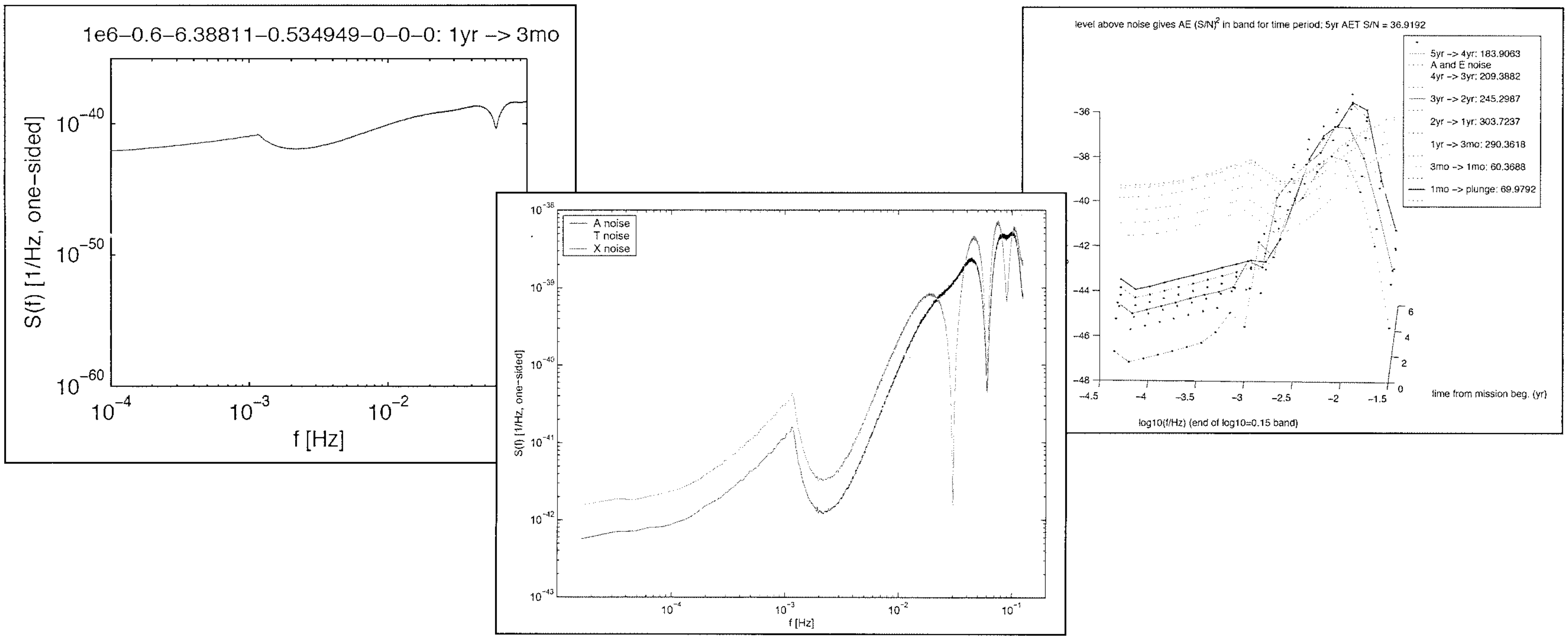
# samples requested, sampling time

# Comparison with LISA Simulator



# Case study: S/Ns for extreme-mass ratio inspirals

Hughes-Glampedakis-Kennefick integrator (C++): output $h_+$, $h_x$ → (Python) → Synthetic LISA: generate A, E, T, X GW & noise time series → Matlab: compute S/Ns



# Summary!

- *Synthetic LISA* is the package I would have wanted to download and use, had I not written it
- *Synthetic LISA* simulates LISA fundamental noises and GW response at the level of science/technical requirements
- *Synthetic LISA* includes a full model of the LISA science process (2nd-generation TDI, laser-noise subtraction)
- *Synthetic LISA*'s modular design allows easy interfacing to extended modeling and data-analysis applications
- *Synthetic LISA* is user-friendly and extensible (C++, Python, other scripting languages)
- *Synthetic LISA* is planned for open-source release in Jan/Feb (NASA permitting)

# Synthetic LISA

## simulating time-delay interferometry in a model LISA


Michele Vallisneri
Jet Propulsion Laboratory


12/17/2003